THE UNIVERSITY OF BRITISH COLUMBIA

INSTITUTE OF PARTICLE PHYSICS

Dark sector searches at Belle II

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Collider Physics in the Northwest 2026

The most compelling question in particle physics

- Much of the universe is composed of matter that does not interact with photons, and is not consistent with the standard model.

Cluster MACS J0025.4-1222. Blue shows mass distribution from gravitational lensing; red shows ordinary matter from x-ray imaging

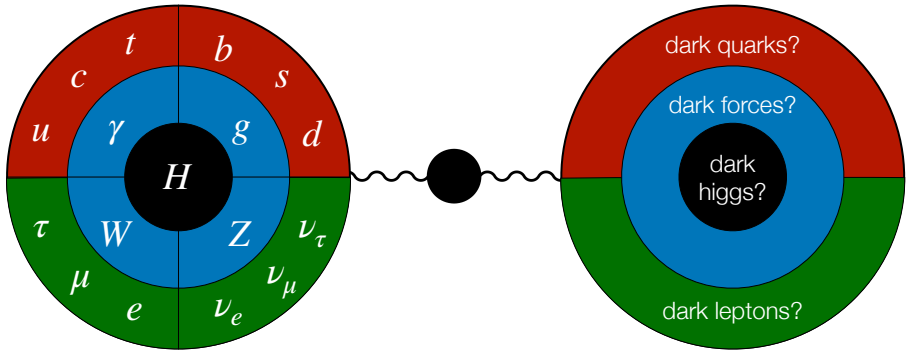
NASA, ESA, CXC, M. Bradac, and S. Allen

- What is the particle nature of dark matter?

The dark sector

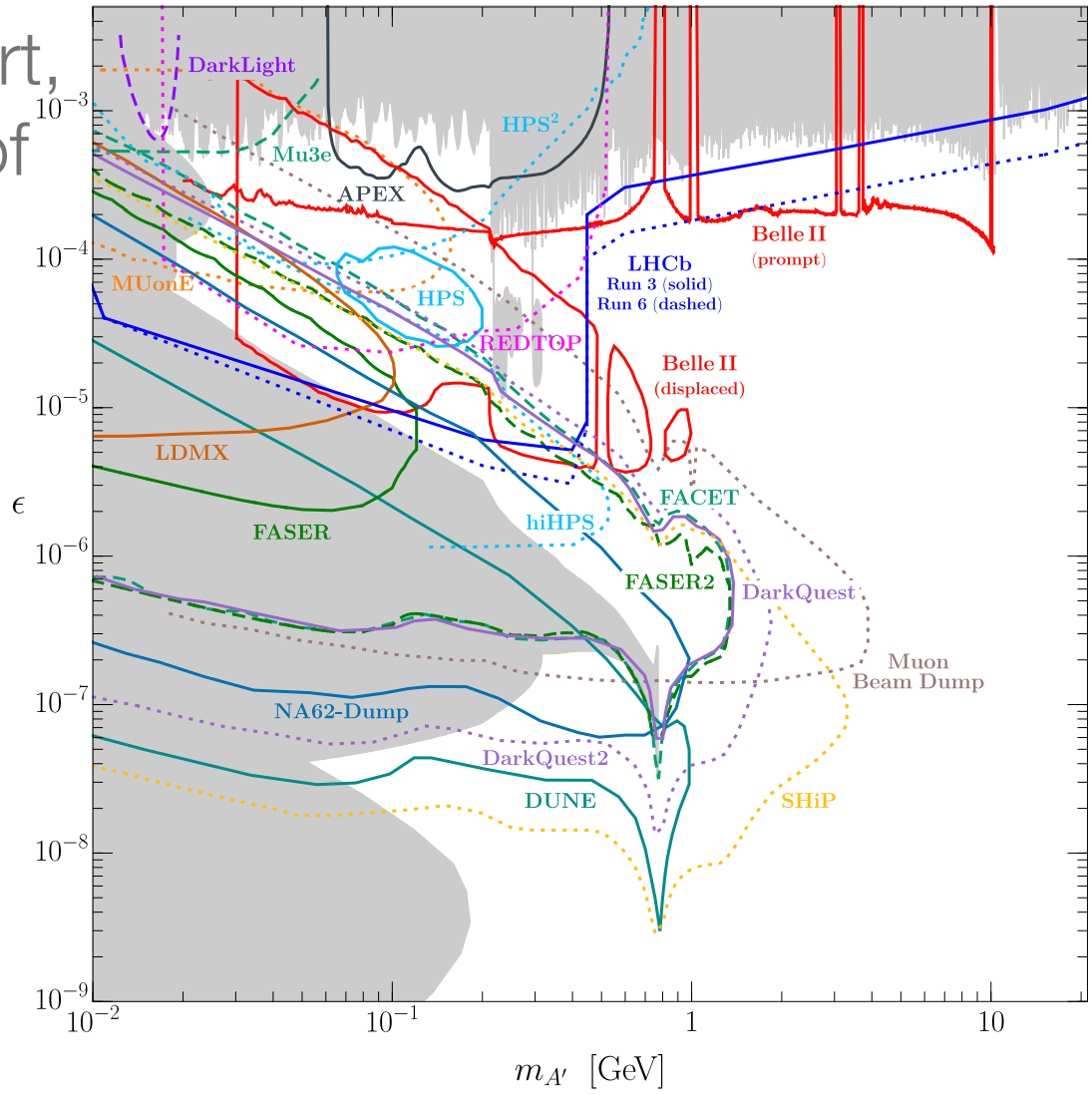
- Currently, there is considerable focus on “dark sector” models of dark matter.
  - Dark matter particles are light, typically < few GeV/c^2
  - Requires new dark force carriers, which have feeble interactions with the standard model.

Gori, Williams et al,
arXiv 2209.04671 (2022)



Searching for the dark sector in the laboratory

- Extensive, world-wide effort, including a large number of dedicated projects.



Batell, Blinov, Hearty, McGehee,
arXiv 2207.06905 (2022)

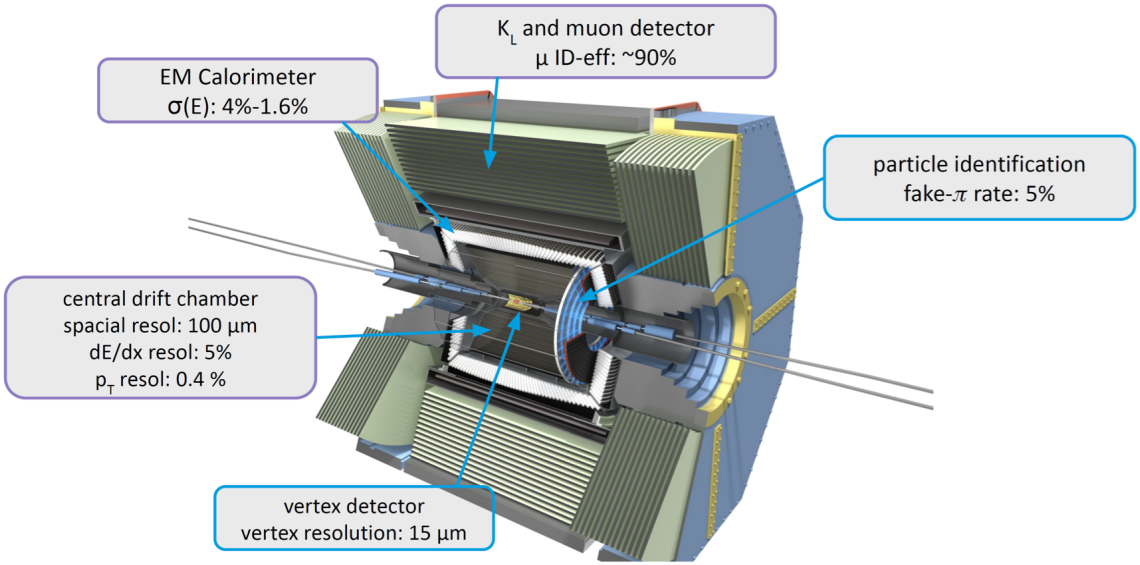
Outline

- Belle II and SuperKEKB
- Dark sector searches — overview
- Dark photon / with dark Higgs
- L_μ - L_τ Z'
- Axion-like particles

Belle II and SuperKEKB

Belle II at the SuperKEKB e^+e^- collider in Tsukuba, Japan

- Almost total upgrade of Belle for better performance and higher rate capabilities.

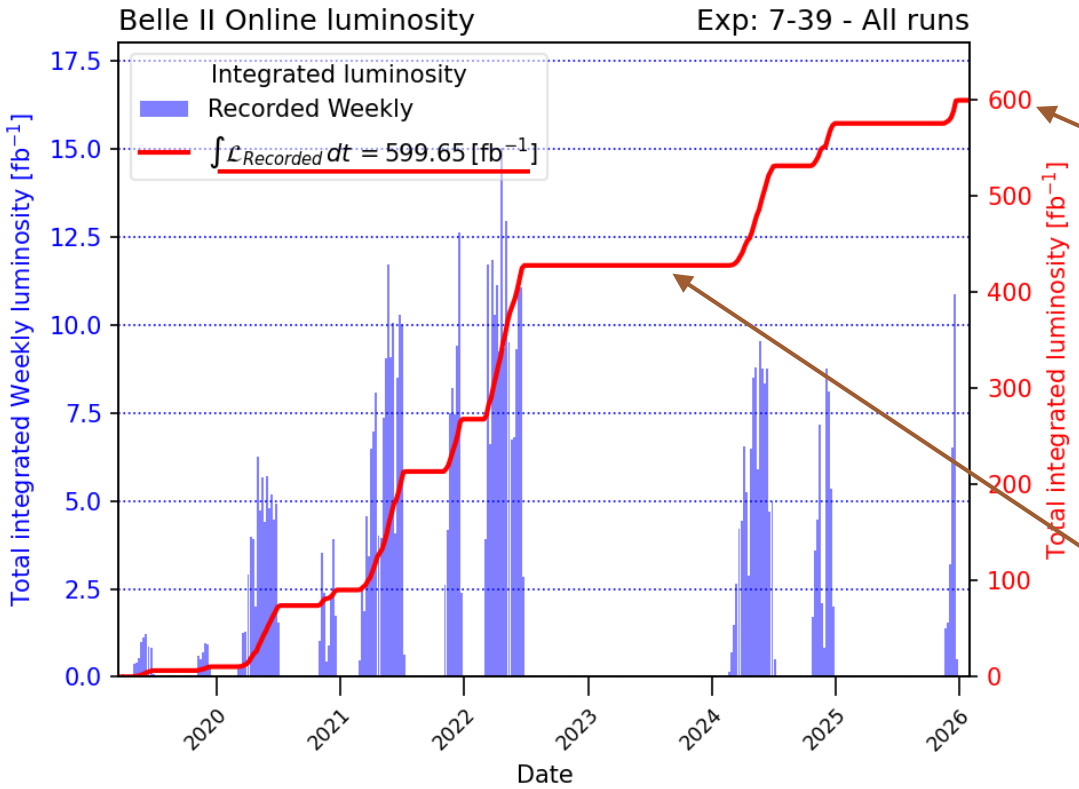


- Better vertex tracking;
  Much larger drift chamber ⇒ excellent momentum and mass resolution;
  Advanced particle identification (π / K separation).

- Key for dark sector:
  - clean e^+e^- environment;
  - loose triggers (single γ, single track); currently, some are very loose. Displaced vertex under development.
  - (in the long run) high luminosity.

SuperKEKB

- World's highest instantaneous luminosity collider, 5×10^{34} cm^{-2}s^{-1}. But slow progress towards target of 6×10^{35} cm^{-2}s^{-1}.



total = 600 fb^{-1};
BaBar 500 fb^{-1}
Belle 1000 fb^{-1}
goal: 50,000 fb^{-1}

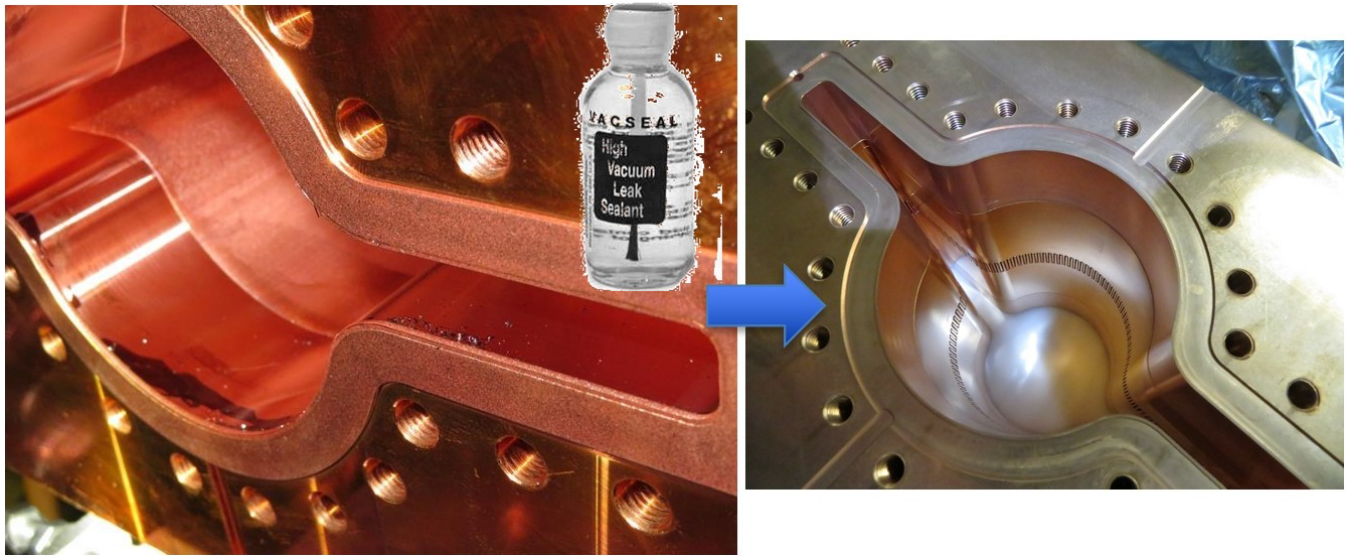
long shutdown 1 to install two-layer pixel detector

- Issues include:
  - Low injection efficiency (high backgrounds, lower beam current);
  - Beam-beam interactions that prevent the necessary beam squeezing;
  - Sudden beam loss.

Sudden beam loss

- Operations in 2024 were interrupted by a number of sudden beam losses that deposited large amounts of radiation in the vertex detectors and final focus.
  - Some damage to new pixel detector. Has been off since May 2024.
  - Numerous final focus magnet quenches.

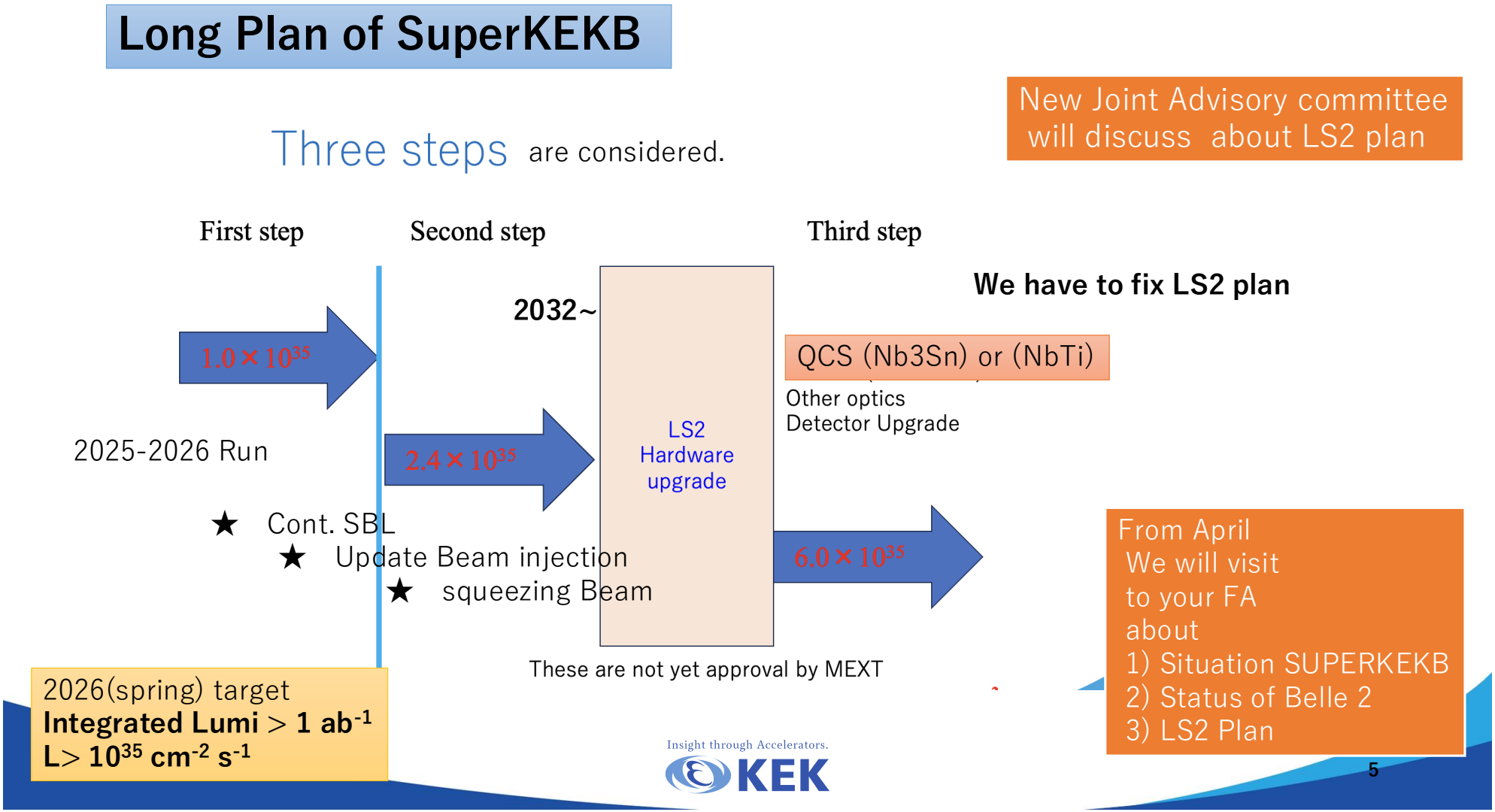
- Major source now understood to be the use of “vacseal” vacuum sealant.



- Cleaning various surfaces has reduced SBL rate by ~6× in 2026 running, but more is needed.

- Various interventions have produced higher overall backgrounds (vacuum quality).

Long range plan — not yet approved



- Long shutdown 2: 2032–2033. Plan is to include new final focus magnets.

- New vertex tracker (acceptance goes from 17° to 20° in forward direction).

- Leaning towards a new drift chamber (lifetime).
  - may replace inner part with a fast timing layer.

- TDR 2027.

Belle II competitiveness

- Although our data set is less than Belle, and comparable to BaBar, we are producing world-class physics:
  - better detector
  - better triggers
  - better analysis techniques

Dark sector searches — overview

Dark sector searches at Belle II

- Most of our searches involve final states that include no more than four particles (“low multiplicity”).

- Signals appear as:
  - a peak in the invariant mass of a pair of standard model particles;
  - a peak in the “missing mass” recoiling against the visible particles; $p_{invisible} = p_{e^+} + p_{e^-} - p_{visible}$
  - or both.

- Dark sector ⇒ feeble connection to standard model ⇒ non-negligible lifetime. Starting to use displaced vertices.

- Some searches in B decays.
  - e.g. couplings to W or top.

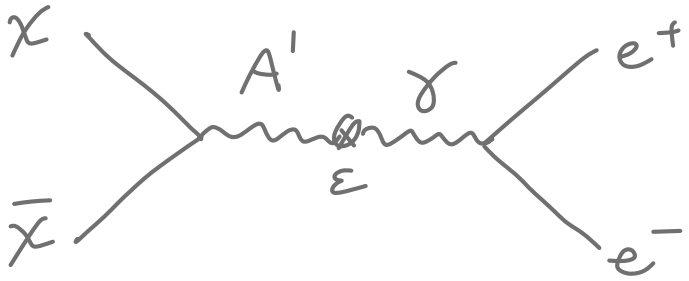
- Analyses are generally optimized and presented in the context of a particular model. I will focus today on more “standard” models; we also have a variety of analyses focused on more exotic cases.

Dark photon / with dark Higgs

Dark matter / dark sector / dark photons

- Particularly straightforward model: dark matter χ plus dark photon A′, which mixes with strength ε with the γ.

- Dark matter is in thermal equilibrium in the early universe



and vice-versa

Different process if $m_\chi > m_{A'}$; less predictive

- The resulting dark matter relic density depends on the parameter $y = \varepsilon^2 \alpha_D (m_\chi / m_{A'})^4$; there are specific combinations of parameters that give the observed value.

coupling of dark photon to dark matter, $\mathcal{O}(1)$

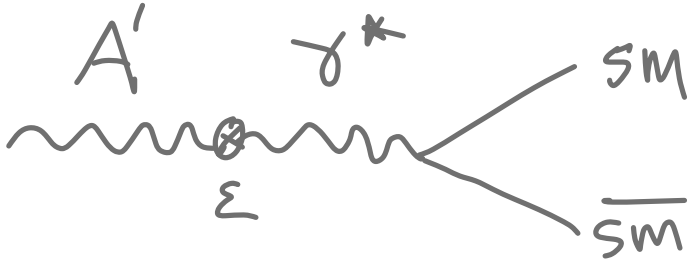
Dark photon production and decay

- So far, we assume dark photon mass < 10 GeV/c^2. Produced on-shell via initial state radiation:

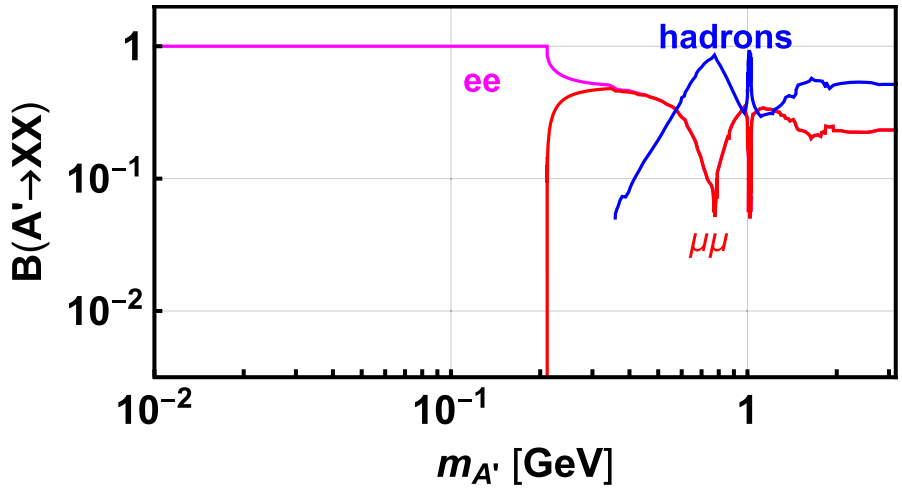
- If kinematically allowed $m_{A'} > 2m_{\chi}$, dark photon decays to dark matter (~100%).

"invisible"

- Otherwise, dark photon decays like a virtual photon of mass $m_{A'}$.

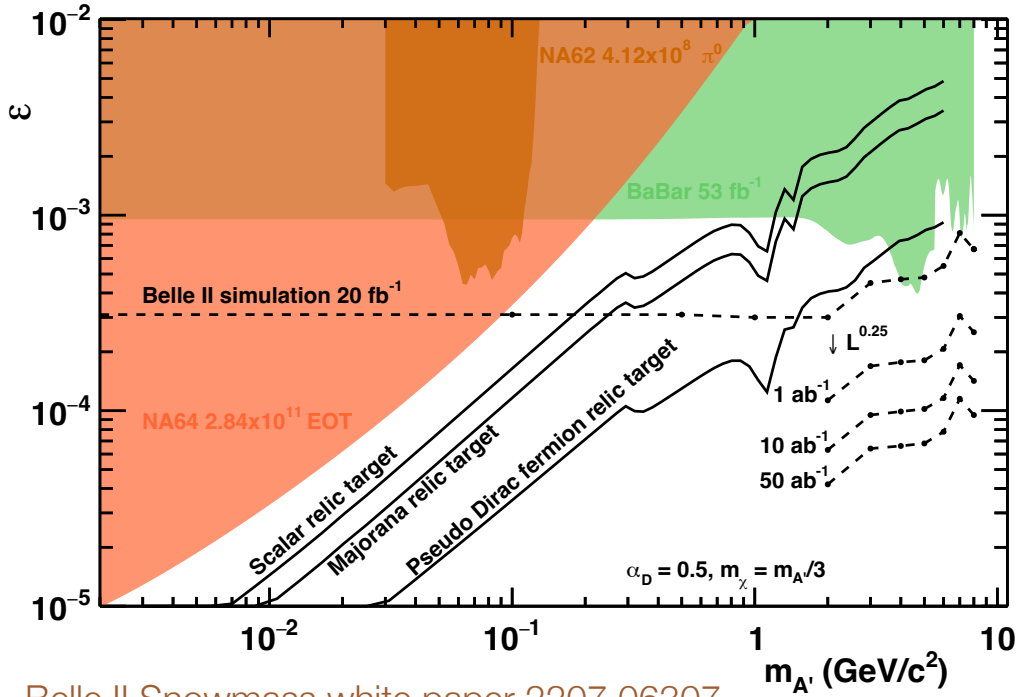


"visible"

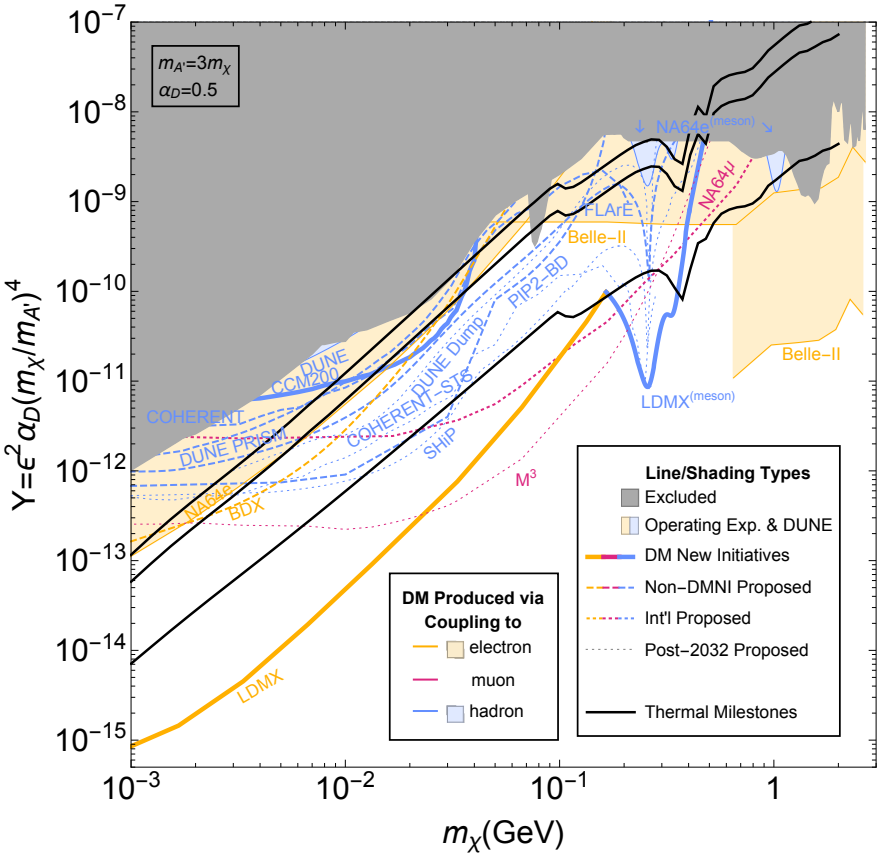


Search for invisible decays of the dark photon (in progress)

- Belle II will have unique sensitivity to regions of parameter space consistent with observed dark matter relic density.



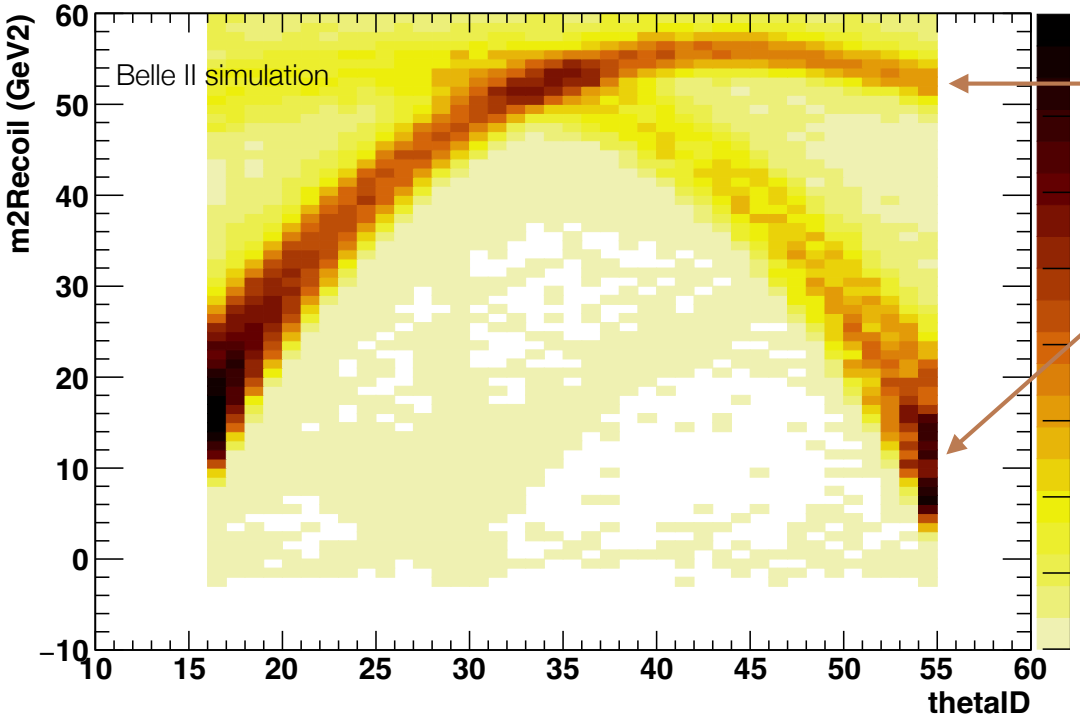
Belle II Snowmass white paper 2207.06307



Snowmass RF6 report 2209.04671

- Challenge is understanding large backgrounds from $e^+e^- \to \gamma\gamma(\gamma)$, where one photon is missed in the detector.
  - especially two body $e^+e^- \to \gamma\gamma$, which looks identical to a low-mass dark photon. Need quantitative prediction of this background.

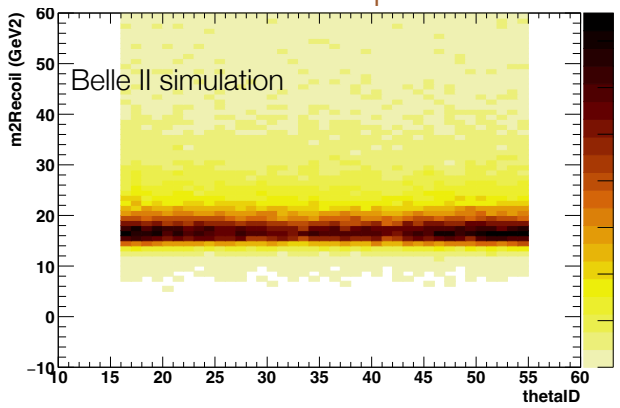
Recoil mass squared vs (approx) θ of the γγ(γ) background



γ down the beam pipe, 2nd γ in backward endcap/barrel gap

γ down the beam pipe, 2nd γ in forward endcap/barrel gap

4 GeV dark photon



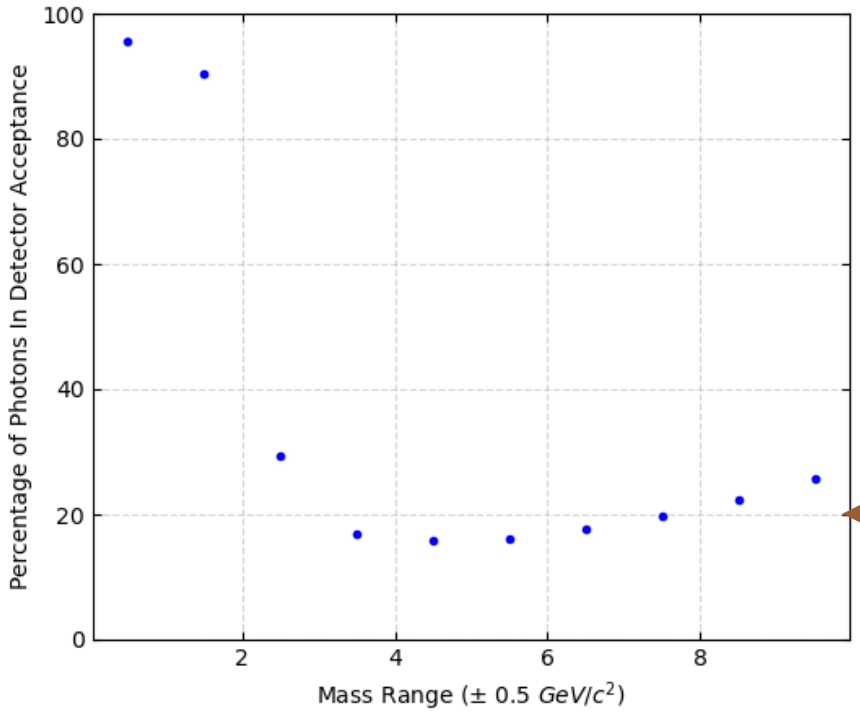
Visible decays of the dark photon (in progress)

- $A' \rightarrow e^+e^-$ search is focused on $m_{A'} < 20$ MeV/c^2.
- ATOMKI has seen an anomaly in ^{8}Be decay to e^+e^- that could be a 17 MeV/c^2 dark photon.
  - DarkLight
- BaBar did not search in this mass range due to a large background from photon conversions to e^+e^- in $e^+e^- \rightarrow \gamma\gamma$.
- Machine learning techniques to suppress this background seem promising.

- $A' \rightarrow \mu^+\mu^-$ approach is different from BaBar; no attempt to reconstruct the photon.

- Slightly higher backgrounds, and slightly degraded mass resolution, but big increase in statistics.

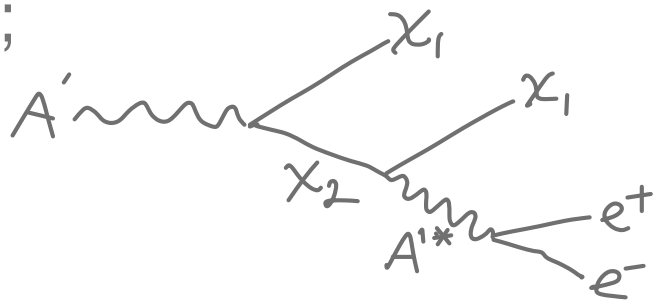
fraction of ISR photons in detector acceptance vs dark photon mass



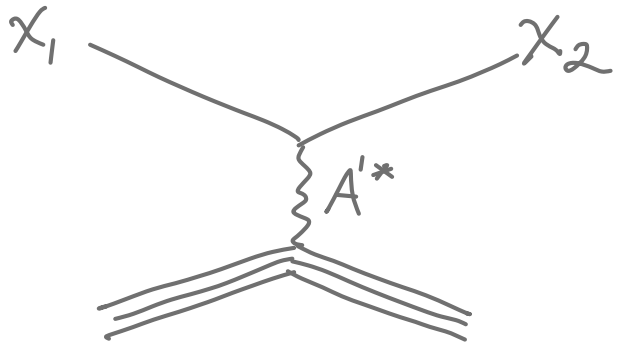
factor of 5 increase in stats

Inelastic dark matter — semi-visible

- Dark photon could couple to a pair of particles $\chi_1\chi_2$.
  - χ_1 is the astronomical dark matter;
  - χ_2 is slightly heavier, and decays to χ_1 plus standard model particles.

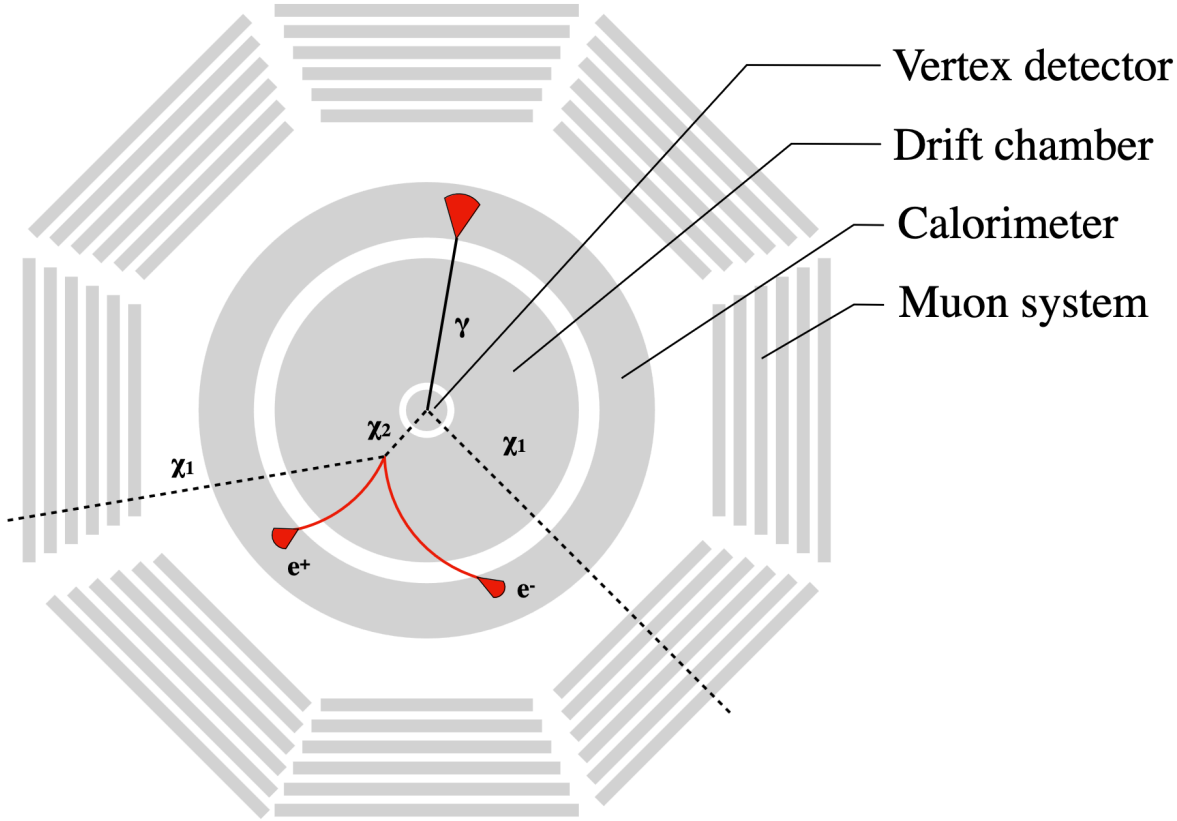


- Can explain the observed dark matter relic density, and also the lack of a signal in direct detection.



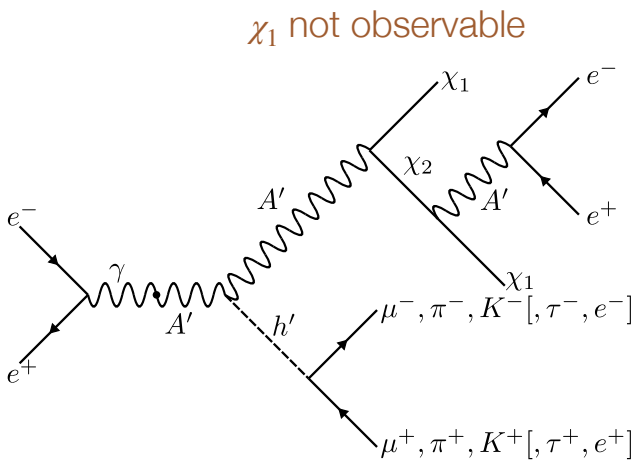
production of heavier χ_2 is kinematically forbidden for low-momentum χ_1.

- Signature is ISR photon plus displaced, non-pointing vertex. Not covered by previous searches.



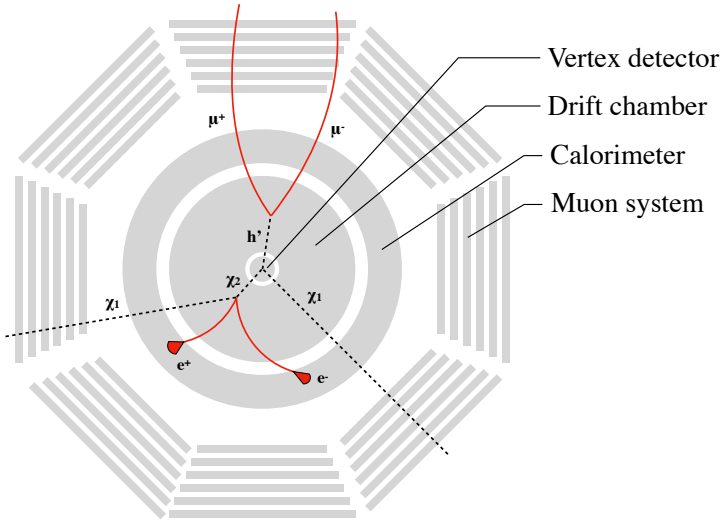
Inelastic dark matter plus dark Higgs at Belle II

- Assume that the dark sector includes a dark Higgs h′. Mixes with strength θ with the Higgs.



trigger on calorimeter energy from e^+e^-; displaced vertex trigger under development

reconstructs to h′ mass

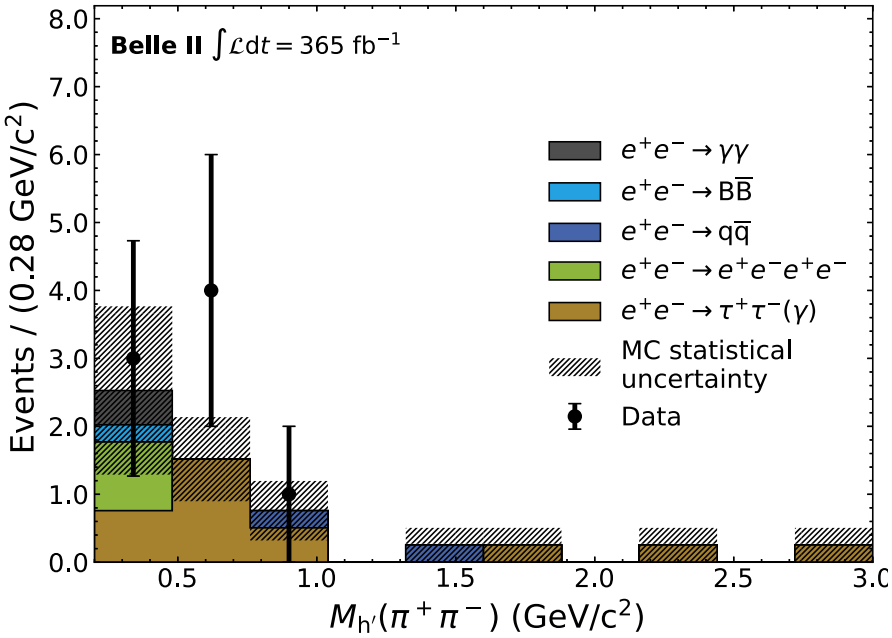


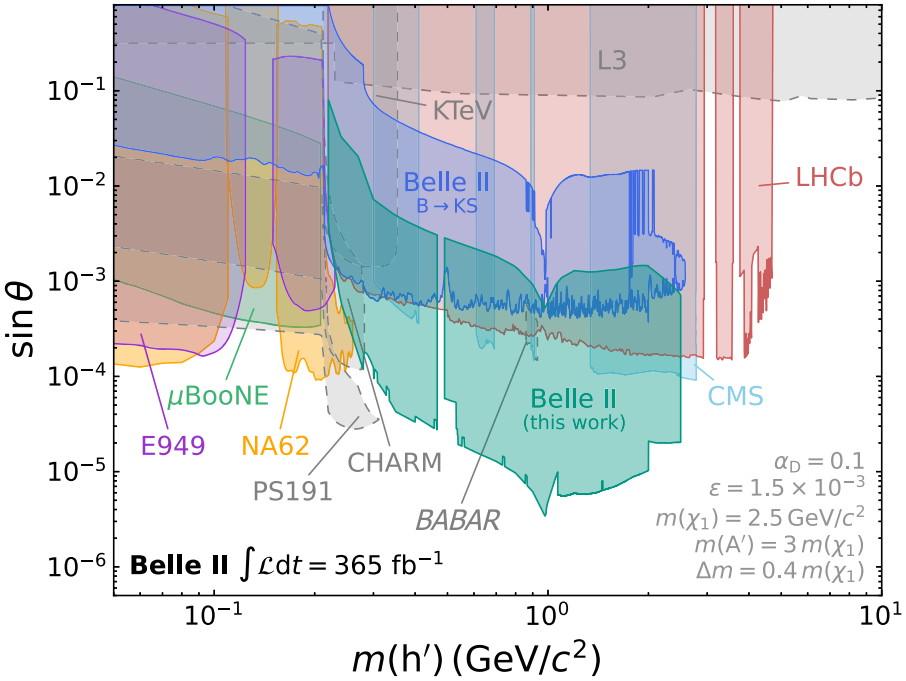
Duerr, Ferber et al, JHEP04 (2021) 146

- Very low backgrounds; displaced vertex plus energetic e^+e^- pair with opening angle not consistent with a $\gamma \to e^+e^-$ conversion.

9 events observed, consistent with expected background.

8 of 9 are $\pi^+\pi^-$





non-Belle II limits do not require A′ or iDM

$L_\mu - L_\tau$ Z'

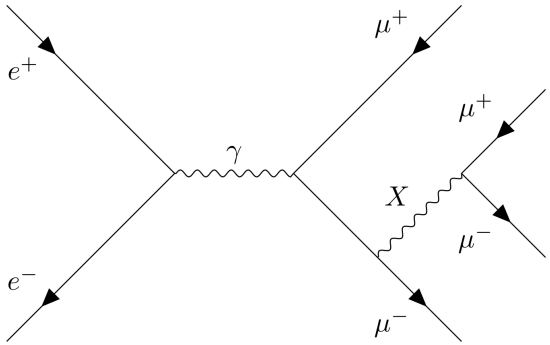
The L_μ - L_τ model

- I motivated this talk with dark matter. But perhaps there are other hints of new physics.
  - Muon anomalous magnetic moment $(g-2)_\mu$;
  - Observables in the B system, e.g. angular distributions in $B \to K^{(*)}\mu^+\mu^-$.
- The L_μ - L_τ model includes a gauge boson Z′ that couples only to mu or tau leptons or neutrinos.
  - could also couple to dark matter.

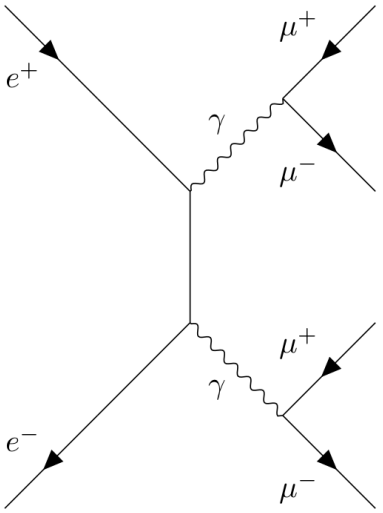
PRD 109, 112015 (2024)

Search for a $\mu^+\mu^-$ resonance in four-muon final states at Belle II

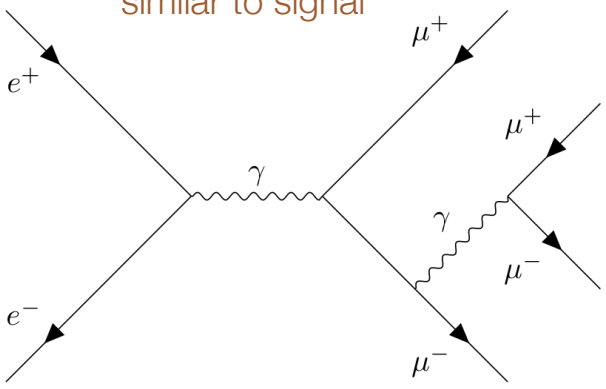
- Search for resonance in 4μ events.
- Same signature for muonphilic scalar. Created to explain $(g\text{-}2)_\mu$.



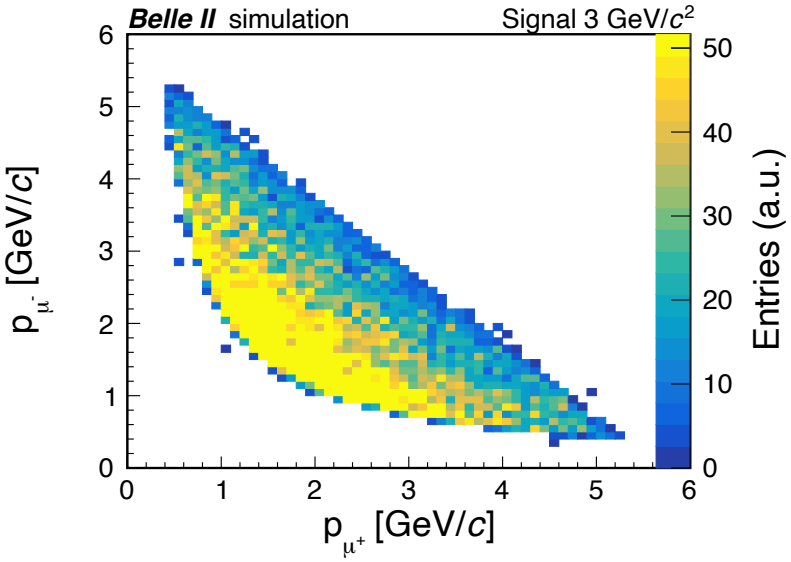
- Large standard model production of $e^+e^- \to \mu^+\mu^-\mu^+\mu^-$:

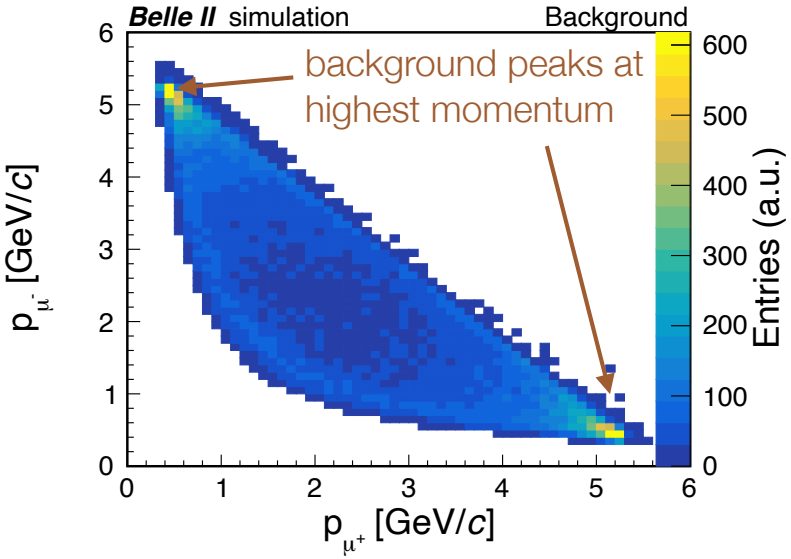


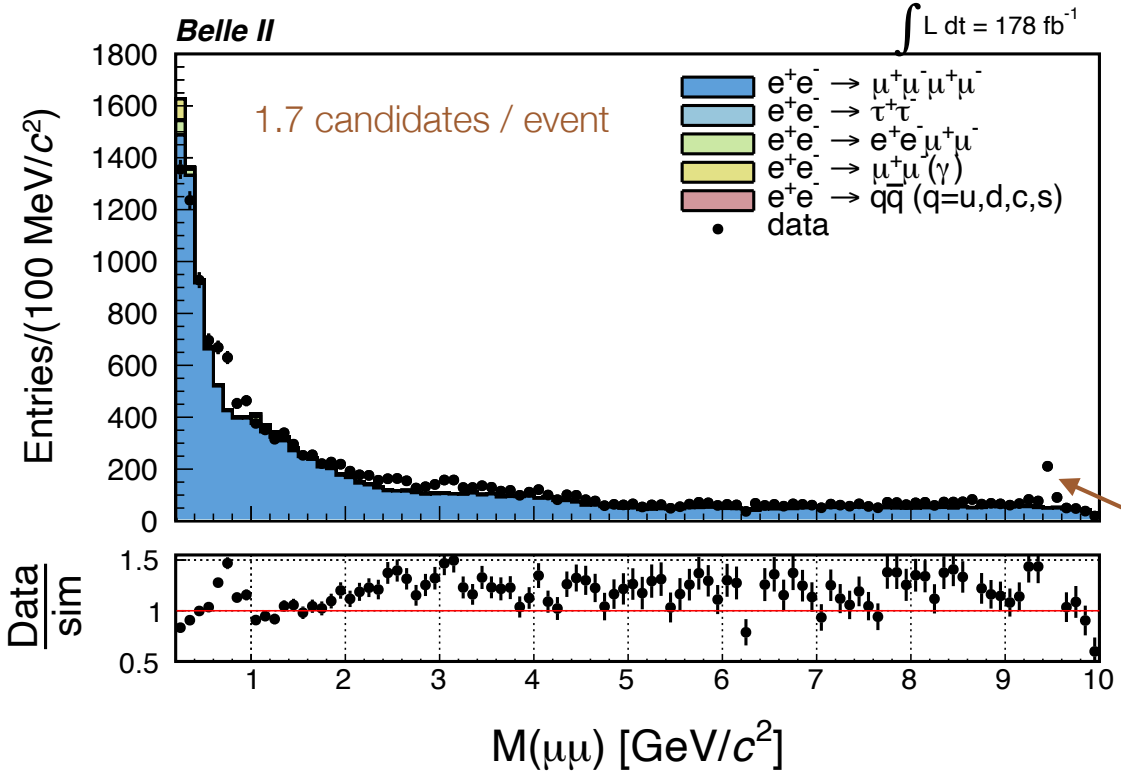
subdominant, but kinematically similar to signal



- Key: exploit kinematic differences between the signal (i.e. final state radiation) and most of the background in a neural net.
  - trained on Z′, applied to scalar.

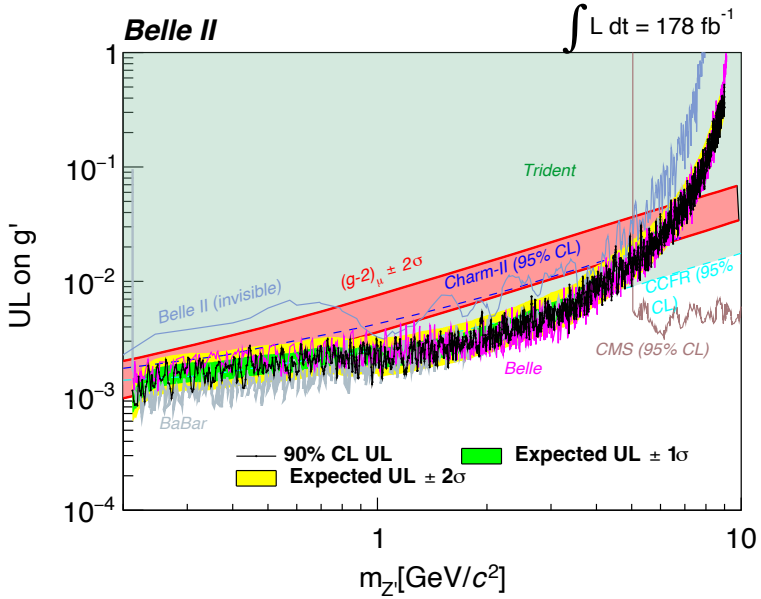


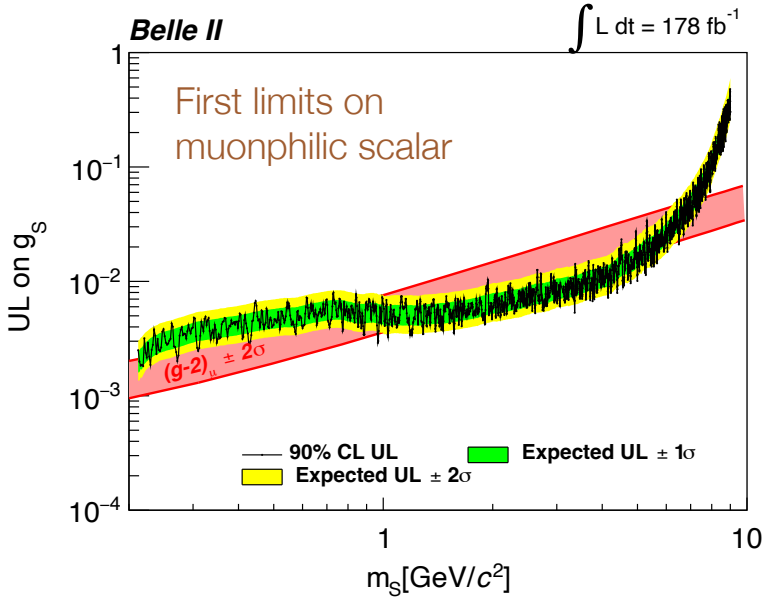




$\Upsilon(4S) \to \Upsilon(1S)\pi^+\pi^-$

- Z′ limits are comparable to BaBar with 1/3rd of the luminosity due to machine learning discriminator.
- First limits on muonphilic scalar; exclude part of $(g\text{-}2)_\mu$ parameter space.





Phys. Rev. Lett. 130 (2023) 231801

Search for an Invisible Z^0 in a Final State with Two Muons and Missing Energy at Belle II

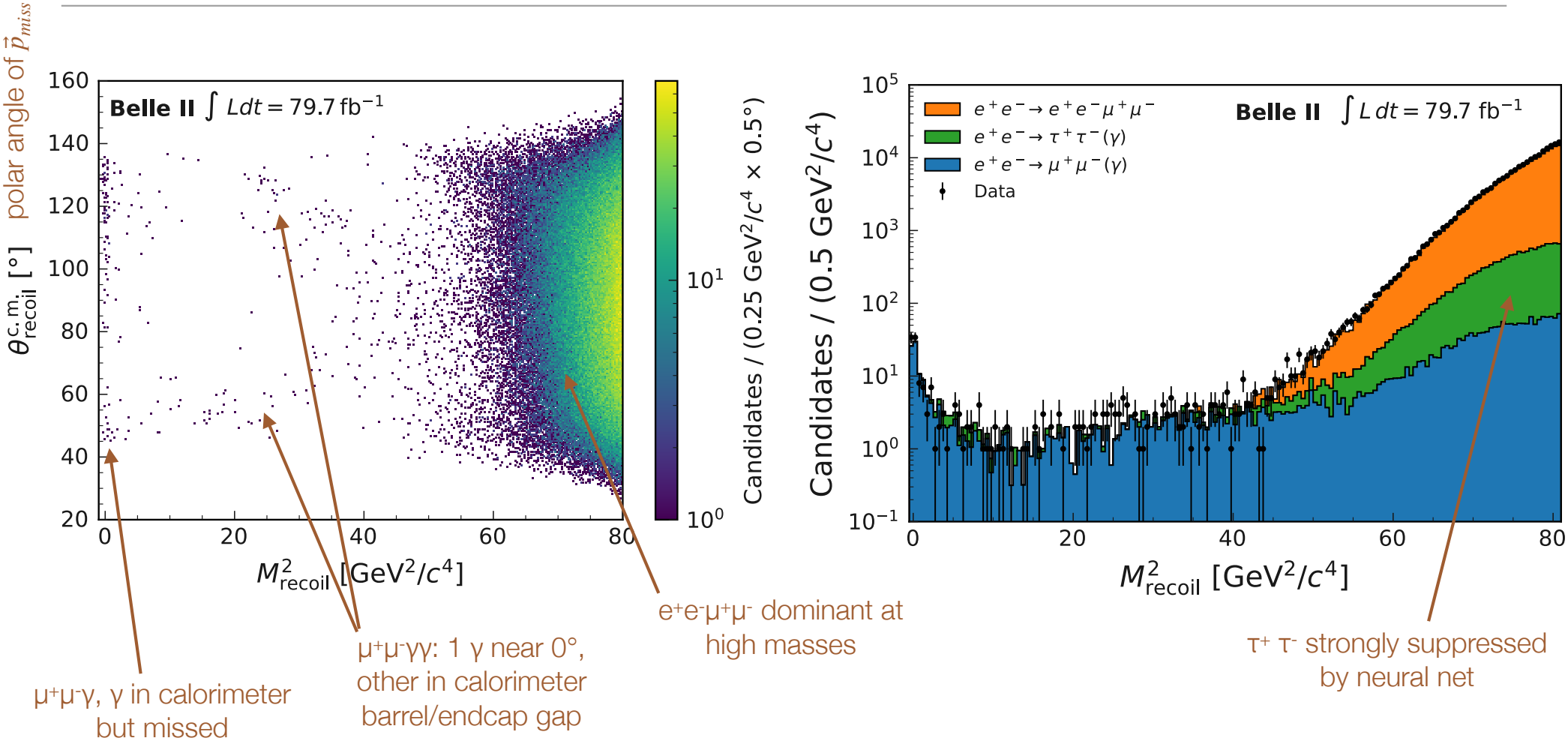
- Signature: pair of muons with missing mass = $m_{Z'}$.

- Backgrounds:
  - $\tau^+\tau^-$, with both $\tau \to \mu\nu\bar{\nu}$;
  - $\mu^+\mu^-\gamma$;
  - $\mu^+\mu^-\gamma\gamma$;
  - $\mu^+\mu^- e^+e^-$;

- As for the visible case, train neural net to identify characteristic kinematics.

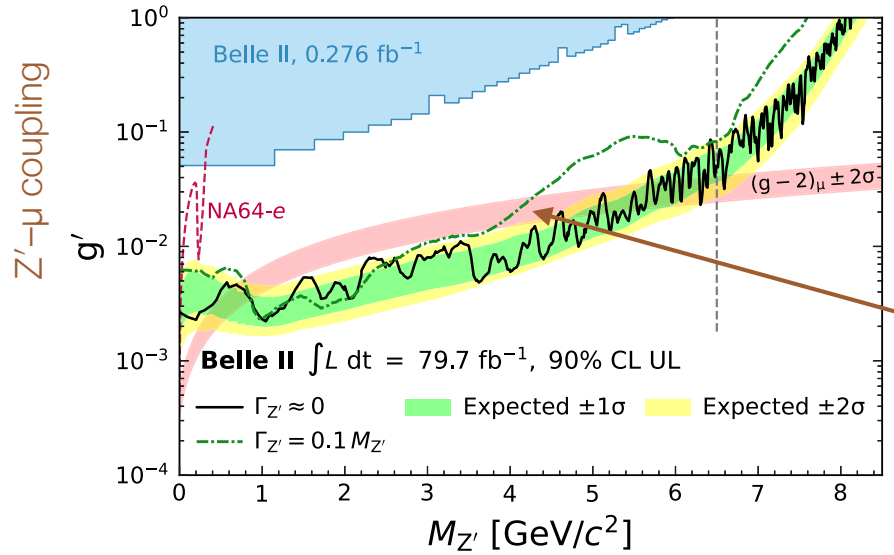
Phys. Rev. Lett. 130 (2023) 231801

$Z' \rightarrow$ invisible selected events



$Z' \rightarrow$ invisible results, $\mathcal{B}(Z' \rightarrow \text{invisible}) = 1$

- Fit 2D distribution θ^{cm}_{recoil} vs M^2_{recoil}; no excess observed.



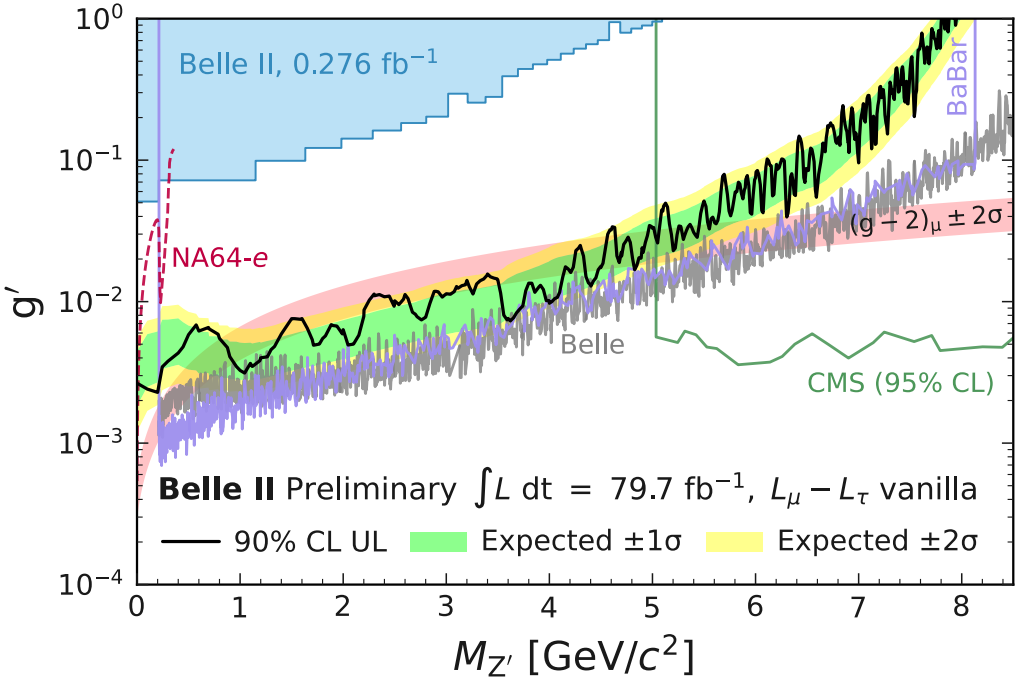
Excludes $(g-2)_\mu$ parameter space for $0.8 < M_{Z'} < 5.0$ GeV/c^2.

- For $Z' \rightarrow$ SM, limits from muons are much better, except below $2m_\mu$.

- Current iteration uses muon system to veto missed γ.

Z′ results, Z′ → standard model only

- If Z′ decays only to standard model particles, limits improved below $2m_\mu$.



Axion-like particles

Axion-like particles

- Axions were proposed to explain why QCD does not violate CP. Axion-like particles have the same quantum numbers, but wider range of masses and couplings, typically to standard model gauge bosons.

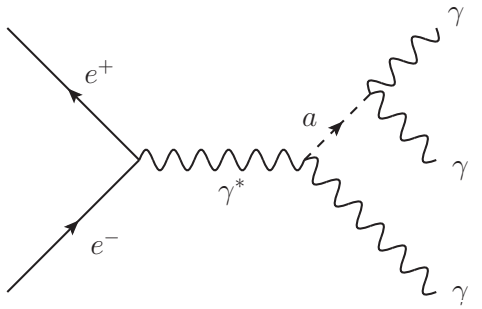
- Could be the mediator to dark matter.

Phys. Rev. Lett. 125 (2020) 161806

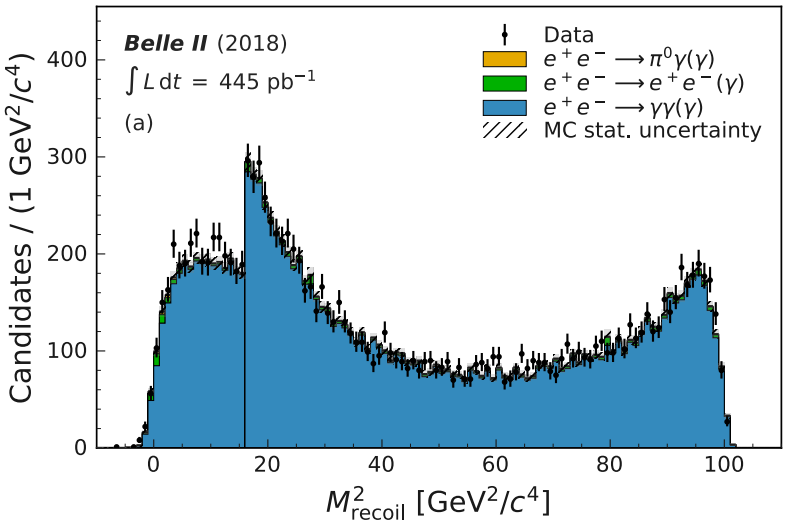
Search for Axion-like Particles Produced in e^+e^- Collisions at Belle II

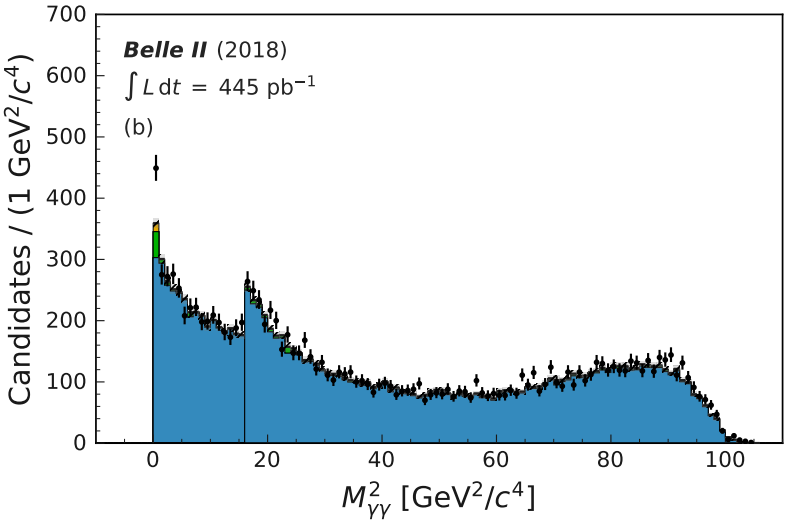
- Assumes coupling to photons is dominant.

- 3γ add up to full center-of-mass energy; 2 of which add up to axion-like-particle mass. Large background from $e^+e^- \to \gamma\gamma\gamma$, but no peak in the 2γ spectrum.

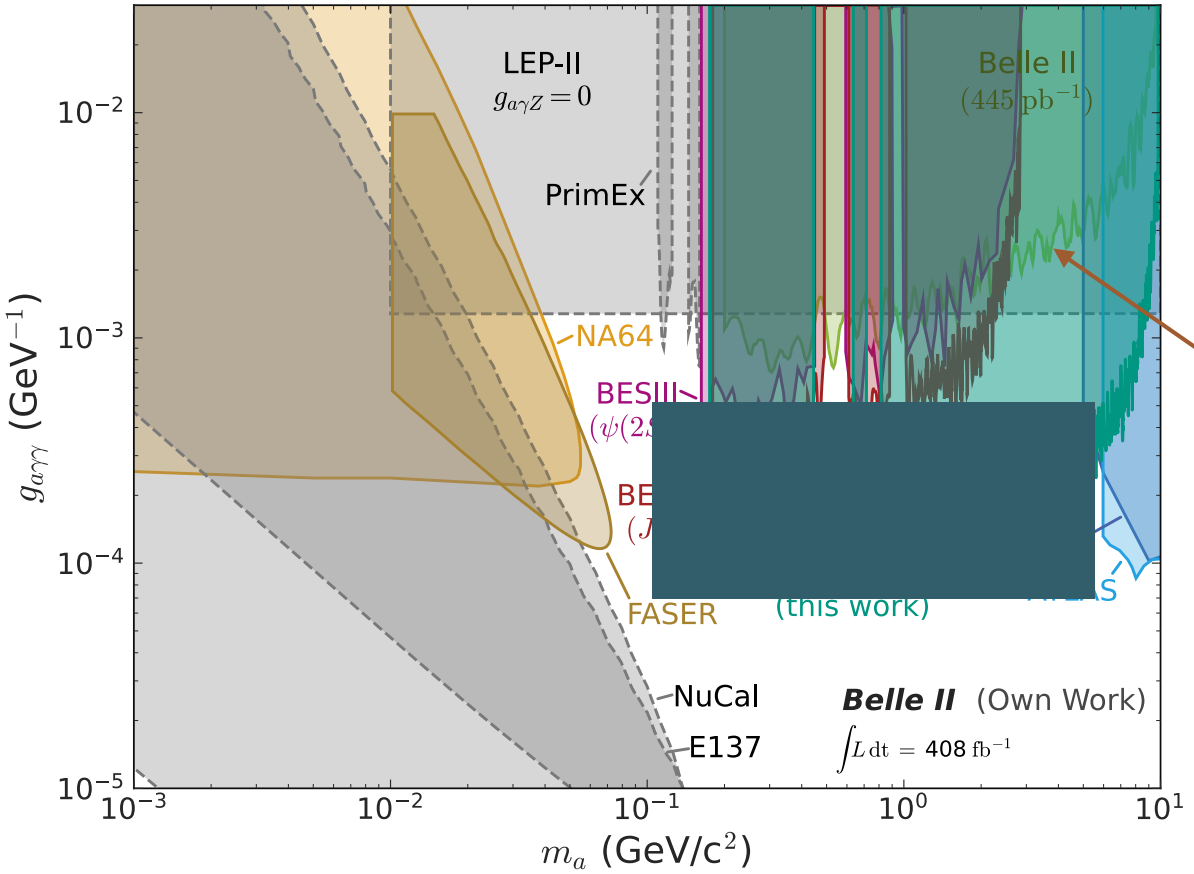


M. Dolan et al, JHEP 12 (2017), 094





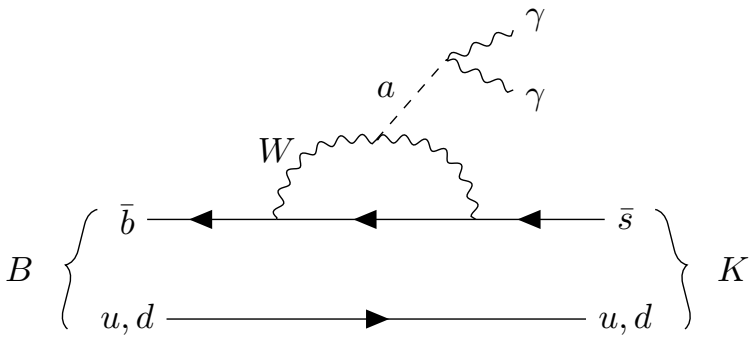
- New results with 900× the data will be public before summer.

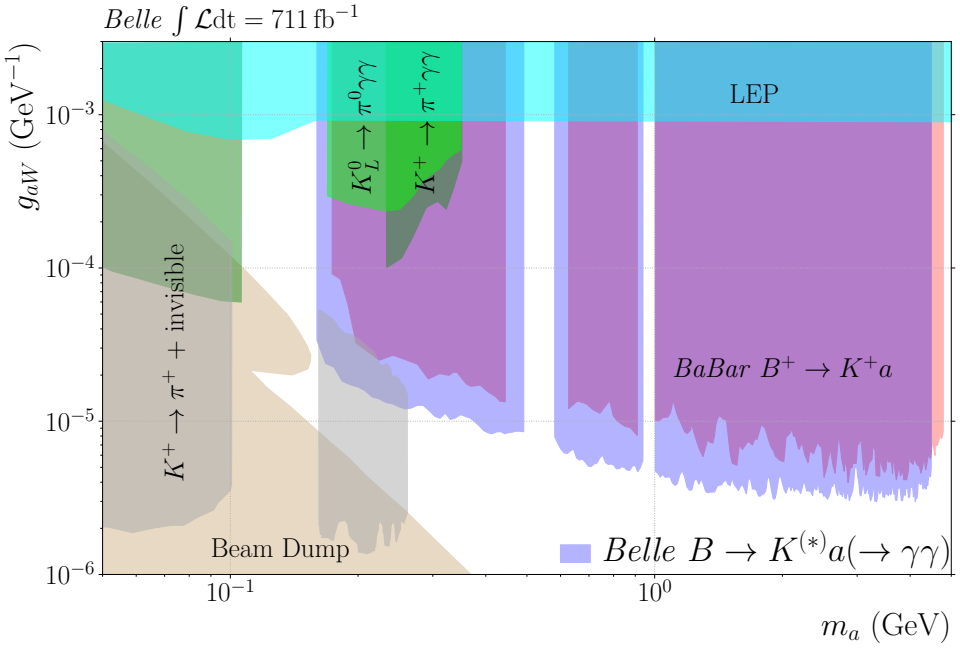


Belle II limits with 0.01% of final data set

Search for an Axion-Like Particle in $B \to K^{(*)}a$, $a \to \gamma\gamma$ Decays at Belle

- Dominant coupling is to the W.
- Four modes: $K^+, K_S^0, K^{*0}, K^{*+}$.
- Machine learning methods to suppress γ from π^0.
- Efficiency degrades at low g_{aW} due to ALP lifetime.

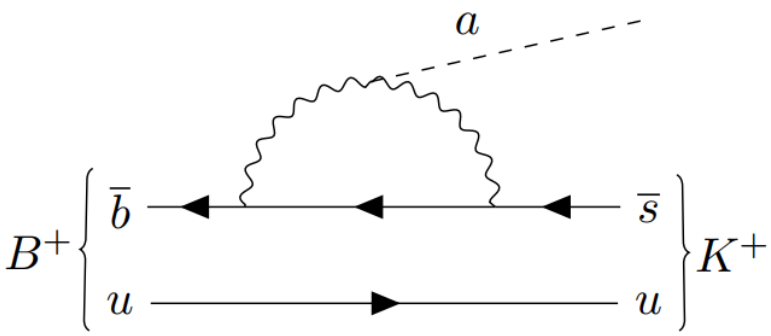




arXiv 2601.07104

A search for feebly-interacting particles in B decays with missing energy at Belle

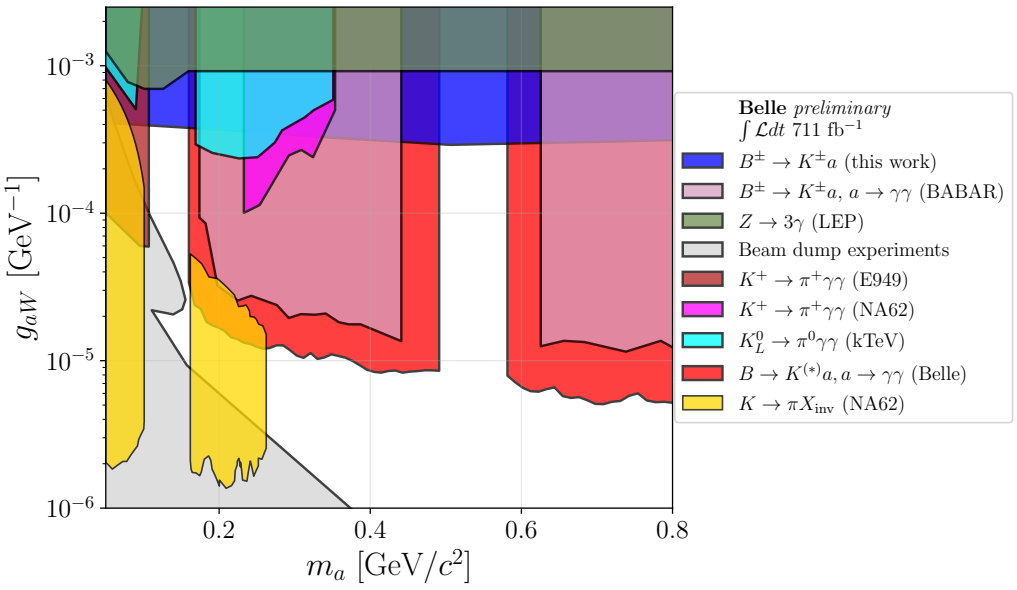
- Two body decay to SM + invisible:
  - $\pi^+, K^+, D_s^+, D^0, p$
  - long-lived or invisible ALP, dark scalar, dark baryon.



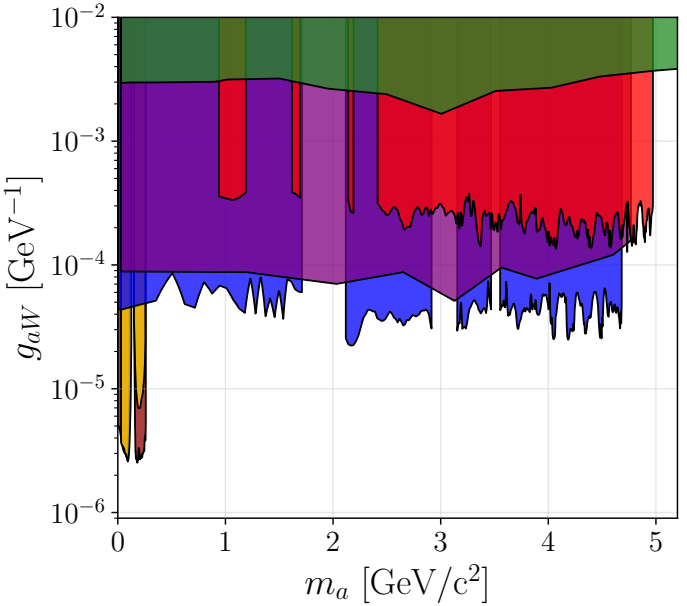
- Fully reconstruct the non-signal B (Philipp Horak, this afternoon). Signal is a peak in the momentum of the visible daughter in B_{signal} frame.

- Limits from $B^+ \to K^+ X_{\text{inv}}$ are especially interesting, given Belle II possible excess in $B^+ \to K^+ \nu\bar{\nu}$.
  - unfortunately, interesting region near 2 GeV/c² is excluded due to backgrounds from $B^+ \to K^+ D^{(*)}$.

limits assuming a→γγ



limits assuming a→ invisible



Summary

- Belle II is producing world-cases dark sector results due to an open trigger, excellent detector, and advanced analysis techniques.

- Current luminosity exceeds BaBar, and we hope to reach Belle this year. Starting to look towards long shutdown 2.

- We are always on the look out for new ideas!